1.0 INTRODUCTION

Submerged Arc Welding (SAW) is an arc welding process wherein the arc is maintained between the continuously fed wire and the work-piece under some granulated flux (Figure 1). The flux keeps the arc and the liquid pool away from atmospheric contamination and provides an effective heat-insulating shield to the molten weld metal. It also protects the welder from fumes and radiation at the time of welding. The flux composition influences arc stability, cleanliness, appearance and composition & the properties of the weld pool. The deposition rate of SAW process is very high, which makes its suitable for joining thick sections, overlaying and re-building of worn out surfaces in a very cost-effective manner.

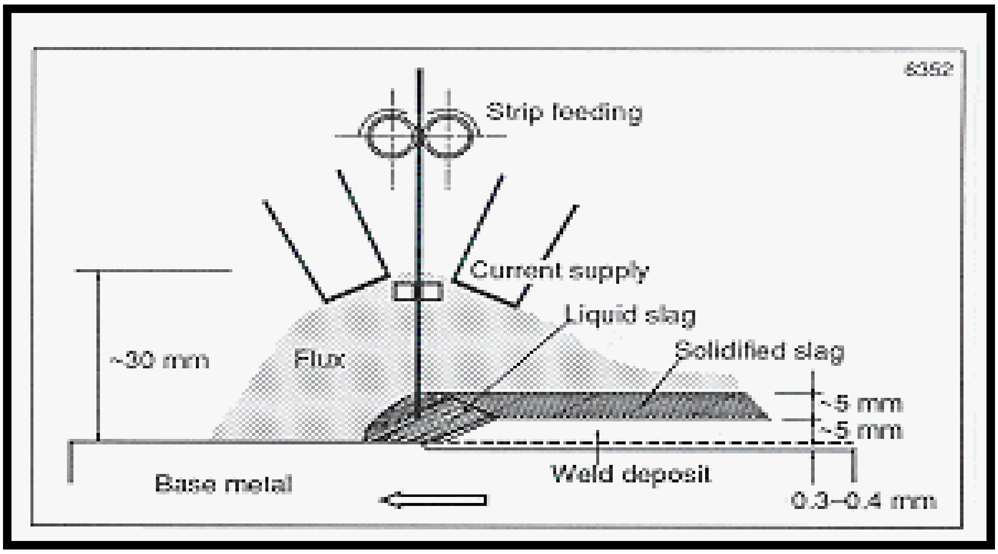

Figure: 1 Schematic sketch of submerged arc welding process (from internet)

2.0 CLASSIFICATION OF FLUX

Depending on the manufacturing process, the SAW fluxes are classified into two types, fused and agglomerated. Melting the dry-mixed ingredients in a furnace makes fused fluxes. The molten mass is rapidly cooled, crushed and packaged after suitable screening. The powdered ingredients of an agglomerated flux after dry blending is mixed with some inorganic binders and palletized followed by drying in an oven (700 – 800°C). Because of lower manufacturing temperature, agglomerated flux is chemically more active and contains de-oxidizers and ferro-alloys.

Fused fluxes are dark brown or black in colour with a glass-like surface and flakey in shape. Fused fluxes are general purpose fluxes that require no preheating.

Agglomerated fluxes are light in colour and roughly spherical in shape. They give the best mechanical properties and low hydrogen weld metal. Agglomerated fluxes absorb moisture so, they must be re-dried prior to use. Generally re-drying of the flux is done by heating the flux at 350°C and holding for a minimum period of one hour.

Again based on basicity index (BI), SAW fluxes are also classified into acidic, neutral and basic types. The BI according to T. Boniszewski, is given by the ratio-

$$\text{Basicity} = \frac{[CaO+CaF_2+MgO+K_2O+Li_2O+BaO+SrO+0.5\,(MnO+FeO)]}{[SiO_2+0.5(Al_2O_3+TiO_2+ZrO_2)]}$$

Fluxes with a BI value greater than 1.2 is considered as basic and those with BI below 1.0 are called acidic.

Basic fluxes tend to have lower oxygen (O_2) content with good weld metal toughness compared to acidic fluxes (Table-1). Also, as the basicity decreases, the welding characteristics are improved – the arc becomes more stable, weld appearance becomes better and slag removal becomes easier.

Table-1: Basicity, oxygen content and melting temperature of SAW fluxes

Welding flux	Basicity	Weld metal O_2 content	Melting temperature, °C
Acidic	<1.0	≥ 700 ppm	1100 – 1300
Neutral	1.0 – 1.20	500 – 700 ppm	1300 – 1500
Basic	1.20 – 2.00	300 – 500 ppm	>1500
High basic	>2.0	≤ 350 ppm	>1500

3.0 EFFECT OF WELDING PARAMETERS

Selection of the correct welding conditions for given plate thickness & required mechanical properties - joint preparation, adherence to certain welding procedures are very important. The process variables, which have to be considered, are:

1) Electrode polarity
2) Welding current
3) Electrode diameter
4) Arc voltage
5) Welding speed
6) Electrode extension
7) Electrode angle
8) Flux grain size & depth

These are the variables that determine bead size, bead shape, depth of penetration and in some circumstances metallurgical effects such as incidence of cracking, porosity and weld metal composition.

3.1 Electrode polarity

The deepest penetration is obtained with DC reverse polarity (DC electrode positive, DCEP). Also DCEP polarity gives the best surface appearance, bead shape and resistance to porosity.

Direct current straight polarity (DC electrode negative, DCEN) gives faster burn off (about 35%) and shallower penetration since the maximum heat is developed at the tip of the electrode instead of at the surface of the plate. For this reason DCEN polarity is often used for surfacing applications. The flux/wire consumption ratio is less with electrode negative polarity than with electrode positive polarity, so alloying from the flux is reduced.

Alternating current gives a result about half way between DC electrode positive and DC electrode negative and usually gives a flatter, wider bead. It is often used in tandem arc systems where a DC positive electrode is used as the leading electrode and an AC electrode as the trail.

3.2 Welding current

Wire feed speed increases with welding current thus the deposition rate increases as the welding current increases. The wire feed speed is the most influential control of fusion and penetration. The current density (ratio of current & x-sectional area) controls the depth of penetration - the higher the current density the greater is the penetration. For a given flux, a minimum current density is desired for a given electrode diameter to maintain arc stability. Too high a current density leads to instability because the electrode overheats and undercutting may also occur.

3.3 Electrode Diameter

For a given current, changing the electrode diameter will change the current density. Therefore a larger diameter electrode will reduce penetration and the likelihood of burn through but may impose difficulty in arc striking and reduce arc stability.

3.4 Arc voltage

Increase in voltage enhances the melting of the flux. Thus arc voltage can affect weld metal composition. The melting of flux depends on the particle size Too fine flux melts at the edges of the bead and causes sticking problem. With increase in voltage, the width of the slag at the foot of the bead becomes higher (figure-2). The phenomenon leads to more sticking as well as poor slag detachability.

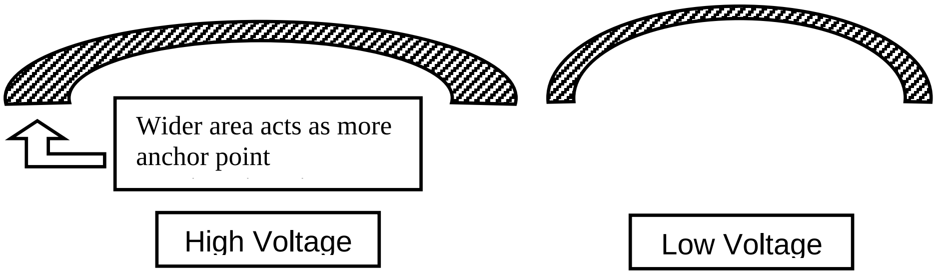

Figure 2: Effect of voltage on flux melting behaviour & bead shape

Arc voltage affects dilution rather than penetration. In a study of bead on plate square edged closed butt welds as the arc voltage increases, width of the bead also increases but depth of penetration remains the same (figure-3). If the joint preparation is open, for example in a butt joint with a small angled 'V' preparation, increasing the arc voltage can decrease the penetration.

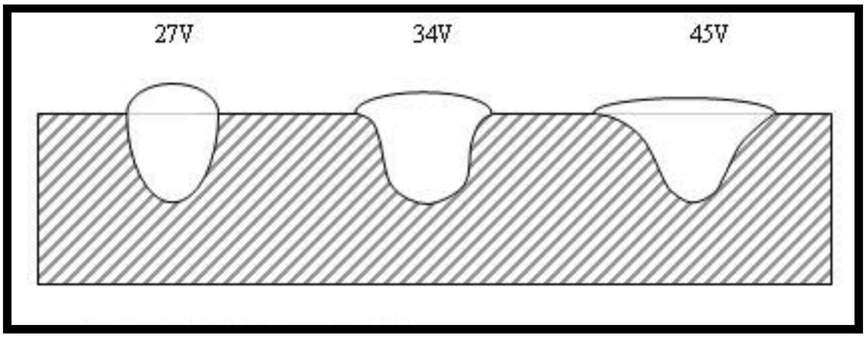

Figure: 3 Schematic depth of penetration in SAW bead with varying weld voltage

3.5 Welding speed

Welding speed or travel speed controls depth of penetration. Bead size is inversely proportional to travel speed. Faster speeds reduce penetration and bead width also increase the likelihood of porosity. In an extreme case may also produce undercut and irregular beads. For slow welding speed burn through can also occur. A combination of high arc voltage and slow welding speed can produce a mushroom shaped weld bead with solidification cracks at the bead sides (figure-4).

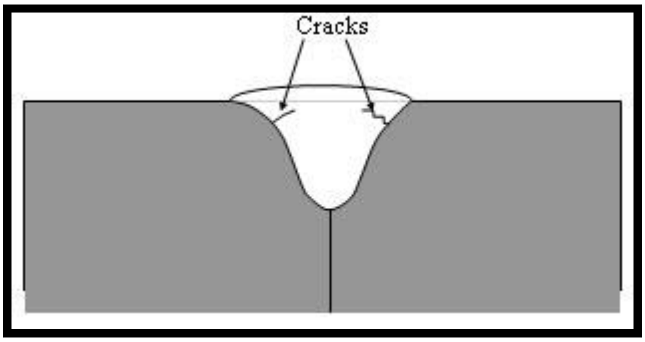

Figure: 4 Schematic sketch of SAW bead profile showing solidification crack

3.6 Electrode extension

The tip to work distance of electrode is known as stick out or electrode extension (EE). EE governs the amount of resistance heating which occurs in the electrode. If the extension is short the heating effect is small and penetration is deep. As extension is increased, the temperature of the electrode rises, which decreases the penetration, but increases deposition rates. Increased extension is therefore useful in cladding and surface applications, but steps have to be taken to guide the electrode, otherwise it wanders.

For normal welding the electrode extension should be 25 - 30mm for mild steel and about 20 - 25mm, for stainless steel. This is because the electrical sensitivity of stainless wire is appreciably greater than that of mild steel wire.

3.7 Electrode angle

The angle between the electrode & the plate determines the direction of the arc force and has a profound effect on both penetration & undercut. The effect of electrode angle on bead profiles is shown in figure-5. The leg lengths of a horizontal fillet vary with the electrode angle.

In a similar way, the trailing torch will provide a deeper penetration compared to a leading or vertical arc. The bead becomes wider for the leading type arc with a shallow penetration. However, the trailing bead suffers from the propensity of undercut.

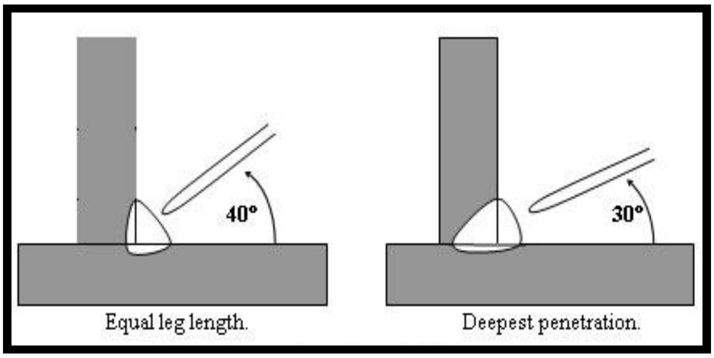

Figure: 5 Variation in leg length with change of electrode angle in HF weld

3.8 Flux grain size & depth

The grain size of the submerged arc welding fluxes lie between 0.20mm to 1.6mm diameter (i.e., between +72 & –10 BSS sieve size). However, the sizes vary depending on the application.

Keeping in mind the higher deposition along with a minimum possible time, often the arc travel speed of the SAW process goes beyond 1.5 meter/ minute. At those conditions proper melting of the flux along with the wire is very critical to achieve the desired performance & weld metal chemistry. Since the arc movement is fast and solidification time becomes low, the size of the grains becomes an important factor. Relatively smaller size grains are preferred for such application considering the ease of melting for its increased surface area. The commonly used particle size of the flux varies between +72 to –14 BSS (0.20 to 1.2mm).

However, when a relatively slower welding speed is adopted (0.50-1.0 meter/ minute) a coarser flux is preferred especially to accommodate some part of the heat of melting ahead of the arc and reduce the flux to wire melt ratio.

The depth of the flux or flux burden is often ignored and the powder heaped around the wire until the arc is completely covered. In order to achieve optimum results, the flux depth should be just sufficient to cover the arc. Too shallow a flux bed gives flash-through and can cause porosity because of inadequate metallurgical protection of the molten metal. Too deep a flux bed gives a poor bead appearance and can lead to spillage on circumferential welds. On deep preparations in thick plate it is particularly important to avoid excessive flux depth otherwise the weld bead shape and slag removal can be unsatisfactory.

4.0 NATURE OF FLUX

Change in the arc voltage during welding changes the quantity of flux interacting with a given quantity of electrode/ wire. This in-turn may change the composition of the weld metal. This change depends on the characteristics of the flux and described as “neutral”, “active” and “alloy”.

4.1 *Neutral flux*

The fluxes those do not produce any significant variation in the weld metal chemistry due to large changes in the arc voltage.

■	The primary use of neutral fluxes is in multi-pass welding especially, when the base metal exceeds 25mm in thickness.
■	Since neutral fluxes contain little or no deoxidizers, they must rely on the electrode to provide de-oxidation. Single-pass welds with insufficient de-oxidation on heavily oxidized base metal may prone to porosity, center-line cracking, or both.
■	Though neutral fluxes maintain the chemical composition even when the voltage is

	changed, it is not always absolutely true. Some of them liberate oxygen on dissociation that may cause reduction in the carbon content of the weld compared to wire, some fluxes contain manganese-silicate which after dissociation may slightly add manganese or silicon in the weld. However, these variations due to changes in voltage are fairly consistent.
■	Also to note that, even when a neutral flux is used to maintain the same chemical composition through a range of voltages, weld properties such as strength & impact properties can change because of changes in other welding parameters such as depth of fusion, heat input, number of passes, etc.

4.2 Active flux

The fluxes those contain small amounts of manganese, silicon or both.

■	The deoxidizers are added to the flux to provide improved resistance to porosity and weld metal cracking caused by contaminants on or in the base metal.
■	The primary use of active fluxes is to make single-pass welds, especially on oxidized base metal.
■	Since active fluxes contain some deoxidizers, the manganese, silicon or both in the weld metal may vary with changes in the arc voltage. An increase in manganese or silicon increases the strength and hardness of the weld metal in multi-pass welds but may lower the impact properties. For this reason, the voltage may need to be more tightly controlled for multi-pass welding with active fluxes than when using neutral fluxes.
■	Some fluxes are more active. They offer more resistance to porosity due to base metal surface oxides in single pass welds than a flux that is less active, but may pose problems in multi-pass welding.

4.3 Alloy flux

The Fluxes contain some alloying ingredients to make alloy weld metal.

■	The primary use of alloy fluxes is to weld low alloy steel and for hard-surfacing.

4.4 Wall Neutrality Number

The Wall Neutrality Number (N) is a convenient relative measure of flux neutrality.

■	It addresses fluxes & electrodes for welding carbon steel with respect to the weld metal manganese and silicon content. It does not address alloy fluxes.
■	For a flux-electrode combination to be considered neutral, it should have a Wall Neutrality Number (N) $\leq$ 35. The lower the number, the more neutral is the flux.
■	For determination of N, a chemical pad of 3 run & 4 layers is made at certain parameter. Then a second weld pad is made keeping all these parameters same but with increase in the voltage by 8 volts.
■	Sample for analyses are collected only from 4th layer and are analyzed for manganese and silicon.
■	The Wall Neutrality Number (N) depends on the change in manganese and silicon regardless whether it increases or decreases. It is an absolute value and is expressed as follows: $$N = 100 (\mid \Delta\%Si \mid + \mid \Delta\%Mn \mid)$$ Where Δ%Si is the difference in silicon content and Δ%Mn is the difference in manganese content in the corresponding two weld pads.

5.0 CLASSIFICATION SYSTEM AS PER AWS STANDARD

<u>Carbon steel electrode & Fluxes</u> (A5.17)

F X X X - E C X X X

(a) (b) (c) (d) (e) (f)

<u>Low alloy steel electrodes & Fluxes</u> (A5.23)

F X X X - E C X X X N - X H X

(a) (b) (c) (d) (e) (f) (g) (h) (i)

(a) Indicates a SAW flux.

(b) Indicates the minimum tensile strength of the weld metal in increments of 10 ksi.

(c) Designates the condition of heat treatment at which the tests are to be conducted. ‘A’ for as-welded condition and ‘P’ for post-weld heat-treated condition.

(d) Indicates the sub-zero temperature (°F) at which the impact strength of the weld metal referred to meets or exceeds 20 ft-lb (27 J). For letter ‘Z’ impact requirements are not defined.

(e) The letter ‘E’ indicates a solid electrode and ‘EC’ indicates a composite electrode.

(f) Classification of the electrode used in producing the weld metal.

Table-1 is for solid Carbon steel electrode, Table-2 is for the composition of solid low alloy steel electrode.

(g) The letter ‘N’ indicates that the weld metal is intended for the core belt region of nuclear reactor vessels. The suffix (N) limits P (0.012% max.), V (0.05% max.) and Cu (0.08% max.).

(h) Indicates the chemical composition of the weld metal obtained with the flux and the electrode.

(i) Indicates the optional requirements of diffusible hydrogen in the deposited weld metal. H4, H8, H16 represents average maximum allowable diffusible hydrogen to be of 4, 8 and 16 ml/100 gm respectively.

Table-1: Composition (wt.%) of solid-carbon steel electrode (SFA-5.17)

AWS class	UNS No.	C	Mn	Si	S, max.	P, max.	Cu., max.	Ti
Low-manganese electrode								
EL8	K01008	0.10	0.25-0.60	0.07 max.	0.030	0.030	0.35	-
EL8K	K01009	0.10	0.25-0.60	0.10-0.25	0.030	0.030	0.35	-
EL12	K01012	0.04-0.14	0.25-0.60	0.10 max.	0.030	0.030	0.35	-
Medium-manganese electrode								
EM11K	K01111	0.07-0.15	1.00-1.50	0.65-0.85	0.030	0.025	0.35	-
EM12	K01112	0.06-0.15	0.80-1.25	0.10 max.	0.030	0.030	0.35	-
EM12K	K01113	0.05-0.15	0.80-1.25	0.10-0.35	0.030	0.030	0.35	-
EM13K	K01313	0.06-0.16	0.90-1.40	0.35-0.75	0.030	0.030	0.35	-
EM14K	K01314	0.06-0.19	0.90-1.40	0.35-0.75	0.025	0.025	0.35	0.03-0.17
EM15K	K01515	0.10-0.20	0.80-1.25	0.10-0.35	0.030	0.030	0.35	-
High-manganese electrode								
EH10K	K01210	0.07-0.15	1.30-1.70	0.05-0.025	0.025	0.025	0.35	-

EH11K	K11140	0.07-0.15	1.40-1.85	0.80-1.15	0.030	0.030	0.35	-
EH12K	K01213	0.06-0.15	1.50-2.00	0.25-0.65	0.025	0.025	0.35	-
EH14	K11585	0.10-0.20	1.70-2.20	0.10 max.	0.030	0.030	0.35	-
EG		Value not specified						

■ Dashed line shows, value not mentioned. ■ Single values shown are maximum percentages.

Table-2: Composition (wt.%) of low-alloy steel solid electrodes (SFA-5.23)

AWS class	UNS No.	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	V
EA1	K11222	0.07-0.17	0.65-1.00	0.20	0.030	0.025	-	-	0.45-0.65	0.35	-
EA2	K11223	0.07-0.17	0.95-1.35	0.20	0.030	0.025	-	-	0.45-0.65	0.35	-
EA3	K11423	0.07-0.17	1.65-2.20	0.20	0.030	0.025	-	-	0.45-0.65	0.35	-
EA3K	K21451	0.07-0.12	1.60-2.10	0.50-0.80	0.025	0.025	-	-	0.40-0.60	0.35	-
EA4	K11424	0.07-0.17	1.20-1.70	0.20	0.030	0.025	-	-	0.45-0.65	0.35	-
EB1	K11043	0.10	0.40-0.80	0.05-0.30	0.025	0.025	0.40-0.75	-	0.45-0.65	0.35	-
EB2	K11172	0.07-0.15	0.45-1.00	0.05-0.30	0.030	0.025	1.00-1.75	-	0.45-0.65	0.35	-
EB2H	K23016	0.28-0.33	0.45-0.65	0.55-0.75	0.015	0.015	1.00-1.50	-	0.40-0.65	0.30	0.20-0.30
EB3	K31115	0.05-0.15	0.40-0.80	0.05-0.30	0.025	0.025	2.25-3.00	-	0.90-1.10	0.35	-
EB5	K12187	0.18-0.23	0.40-0.70	0.40-0.60	0.025	0.025	0.45-0.65	-	0.90-1.20	0.30	-
EB6	S50280	0.10	0.35-0.70	0.05-0.50	0.025	0.025	4.50-6.50	-	0.45-0.70	0.35	-
EB6H	S50180	0.25-0.40	0.75-1.00	0.25-0.50	0.030	0.025	4.80-6.00	-	0.45-0.65	0.35	-
EB8	S50480	0.10	0.30-0.65	0.05-0.50	0.030	0.040	8.00-10.5	-	0.80-1.20	0.35	-
EB9 (*)	S50482	0.07-0.13	1.25	0.30	0.010	0.010	8.00-10.0	1.0	0.80-1.10	0.10	0.15-0.25
ENi1	K11040	0.12	0.75-1.25	0.05-0.30	0.020	0.020	0.15	0.75-1.25	0.30	0.35	-
ENi2	K21010	0.12	0.75-1.25	0.05-0.30	0.020	0.020	-	2.10-2.90	-	0.35	-
ENi3	K31310	0.13	0.60-1.20	0.05-0.30	0.020	0.020	0.15	3.10-3.80	-	0.35	-
ENi4	K11485	0.12-0.19	0.60-1.00	0.10-0.30	0.020	0.015	-	1.60-2.10	0.10-0.30	0.35	-
ENi1K	K11058	0.12	0.80-1.40	0.40-0.80	0.020	0.020	-	0.75-1.25	-	0.35	-
EF1	K11160	0.07-0.15	0.90-1.70	0.15-0.35	0.025	0.025	-	0.95-1.60	0.25-0.55	0.35	-
EF2	K21450	0.10-0.18	1.70-2.40	0.20	0.025	0.025	-	.40-0.80	0.40-0.65	0.35	-
EF3	K21485	0.10-0.18	1.70-2.40	0.30	0.025	0.025	-	0.70-1.10	0.40-0.65	0.35	-
EF4	K12048	0.16-0.23	0.60-0.90	0.15-0.35	0.035	0.025	0.40-0.60	0.40-0.80	0.15-0.30	0.35	-
EF5	K41370	0.10-0.17	1.70-2.20	0.20	0.010	0.010	0.25-0.50	2.30-2.80	0.45-0.65	0.50	-
EF6	K21135	0.07-0.15	1.45-1.90	0.10-0.30	0.015	0.015	0.20-0.55	1.75-2.25	0.40-0.65	0.35	-
EM2 ($)	K10882	0.10	1.25-1.80	0.20-0.60	0.010	0.010	0.30	1.40-2.10	0.25-0.55	0.25	0.05
EM3 ($)	K21015	0.10	1.40-1.80	0.20-0.60	0.010	0.010	0.55	1.90-2.60	0.25-0.65	0.25	0.04
EM4 ($)	K21030	0.10	1.40-1.80	0.20-0.60	0.010	0.010	0.60	2.00-2.80	0.30-0.65	0.25	0.03
EW	K11245	0.12	0.35-0.65	0.20-0.35	0.040	0.030	0.50-0.80	0.40-0.80	-	0.30-0.80	-
EG	-	←Values not specified →									

■ Dashed line shows, value not mentioned. ■ Single values shown are maximum percentages

■ Al, Ti and Zr values are0.10 max.,for EM2, EM3 and EM4 grades.

■ (*) Nb (0.02-0.10), N (0.03-0.07), Al (0.04) ■ ($) Ti (0.10), Zr (0.10), Al (0.10)

- X -